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A new method for combined optimal placement of Phasor and Traditional flow measurement units under contingency of single Phasor measurement unit loss

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A B S T R A C T

Background: The Phasor measurement units (PMU) and Flow measurement units are the devices to measure the basic parameters of the Power system. In that, PMU provides a time tagged data of current, voltage and frequency with their magnitude and phase angles using Global positioning system (GPS). PMUs are known for their active response in data acquisition and communication. Hence, PMU has many advantages and applications in the field of Wide area Monitoring, Protection and Control (WAMPAC) as it is used in issues such as state estimation, load shedding, and analysis of fault. **Objective:** The objective is to place the PMUs in the power system for observability. The vital role is to determine the optimal locations of PMU. In case, for a condition under failure of PMU it is to be handled with combined optimal placement along with the flow measurements in optimal location of a power system for complete observability and to handle the emergency condition on single PMU loss. **Results:** This paper presents Genetic algorithm for optimal placement of PMUs and a new method is proposed for combined optimal placement of PMU and Traditional flow measurements to enhance the observability under contingencies. The Genetic algorithm and the new method are tested in standard IEEE 30 and 118 bus systems. The algorithms are verified in terms of number of PMU, time constraint and the choice of best positions of PMU. **Conclusion:** A systematic procedure is followed to attain an optimal placement for PMUs in the power system. Also the concept is extended to combined optimal placement for single PMU loss. The optimal locations for standard IEEE buses are programmed and obtained. The result witnesses that the number of measurement devices is reduced and as a consequence, it is a cost-effective method with contingency and for complete observability. The results likely provide the enhanced performance of the proposed methods.

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INTRODUCTION

The Wide area monitoring, protection and control (WAMPAC) has a major role in the transition of traditional grids to smart grids with its enormous usages (Phadke.AG *et al*., 2008). The traditional grids faced the complications such as centralised power generation and monitoring with the help of historical data. While considering the smart grids, it has de-centralised and distributed generation of power. Also, in addition the monitoring is held based on the real-time data and the consumer interaction can also be involved in the production. Additionally, these systems provide a time framed information for time synchronization of all the systems in various locations. This has reduced the operating time from several minutes to few microseconds. In this consideration of time synchronization, Phasor Measurement units (PMUs) have a wider hope for the engineering experts and the operators in the power stations. The devices having the time tagged data increases the high precision in the measurement strategy. With this, the communication channels have become more reliable and faster (Johnson *et al*., 2011). Hence, the applications of smart grid, the WAMPAC systems are used capably. Likewise, the WAMPAC has extensive applications. The significant applications of WAMPAC in power systems can be given as, State estimation, load and generation balancing, power flow control, voltage stability assessment, post fault-analysis, oscillation detection, wide area damping control and also there are many favourable applications (Yang. Z *et al*., 2012).

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Phasor Measurement Unit:

The prerequisite quantities of the Wide area monitoring rely on the technology of the data acquisition. By adopting the PMUs at selected locations of a power systems network, PMU is capable of gathering information together with the magnitudes and phase angle of current, voltage and frequency phasor measurements (Saikat Chakrabarti *et al*., 2008). These data are synchronized using Global positioning system (GPS) receivers (Hassan Khorashadi Zadeha *et al*., 2011) for a time period of 1 microsecond and regulates the Wide area monitoring systems. While considering the conventional measurement systems, the remote terminal units (RTUs) are handled for collecting the RMS values of currents and voltages (Abbasy.N.H *et al*., 2009).

For observability of a power system, the PMUs are placed in the substations (Anthony Johnson *et al*., 2011). These placement criteria can be done in several procedures under several algorithms. The placement of PMU can be done at any node or bus present in the power system. But better choice of locations will give better results with lesser number of PMUs, thereby reducing the cost of installation of the PMU. The placement strategy has impacts on the installation cost, commissioning cost, and optimal number of substations, hardware topology and the technical issues based on the PMU type(Saini.R *et al*.,). Under the concept of complete observability, the basic terms used in the placement method are directly observable, indirectly observable and unobservable.

- Directly observable: The bus connected to the PMU is said to be completely sensible. In other words, the required quantity is measured by PMU directly. This is said to be directly observable bus.
- Indirectly observable bus: If a bus with absence of PMU but has one or more connection with PMU connected to another bus is said to be predictable. This is said to be indirectly observable bus.
- Unobservable bus: A bus that is not directly or indirectly connected to PMU and has lack of data is called as unobservable bus.

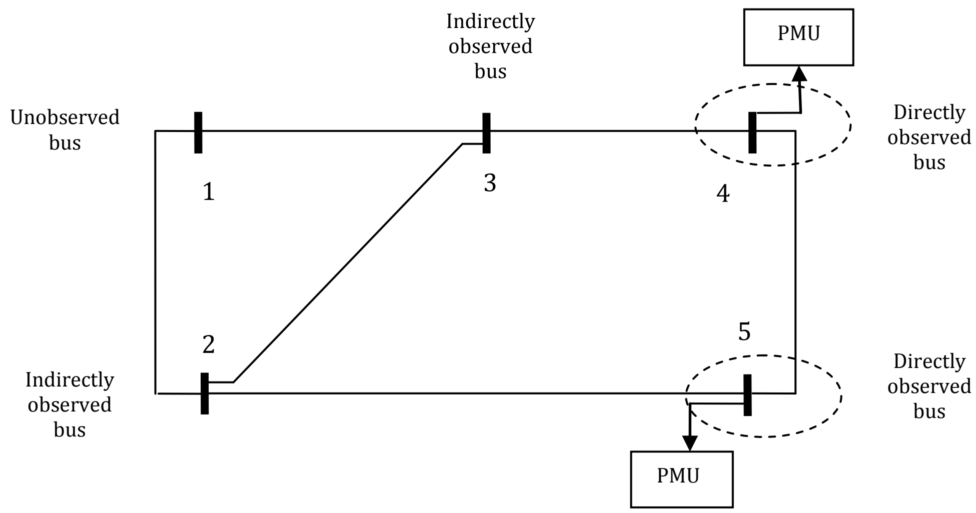

Fig. 1: Diagrammatic representation of PMU observability concept.

With these features, the PMU assists the progress of time recording of a system and dynamic quality of the power systems operating circumstances. From these gathered data, the PMUs increments the efficiency of the operating conditions under normal conditions and also sense the abnormal conditions of the system and rectifies the abnormal conditions. The analysis and detection of the inter area oscillation modes improves the present situations of the system model. Also, the incorporation of PMU in state estimation analysis is reliable and easy. This detects the bad data and enhances the challenges in the state estimator for analytical applications. Likewise, the advantages of PMU extend for many applications in Power system protection.

Optimal Placement of Pmu Using Genetic Algorithm:

GA is the process of exploring a prominent result for a particular scenario. The intention of the GA is to reproduce the natural evolution with the Darwinian principle and hence it is a part of Evolutionary algorithms (Vahidhossein Khiabani *et al*., 2013). The functioning of GA is based on the randomly generated binary strings and the information provided by the strings. It runs for better solution, instead of terminating at a local minimal solution. GA is used for optimization problems for their impressive features and some are listed below,

- For evaluation, GA requires set of chromosomes containing the information of various solutions. GA does not depend on a singular solution.
- Since Darwinian principle about evolution- ‘Survival of fittest’ is used, the fittest individuals will be preferred for the next iteration. Hence, weaker ones will be reduced.

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- GA confides on probabilistic rule and non-deterministic usually.
- Better than traditional methods and easy to understand.

GA can be used for several applications in the field of wide area monitoring and control. The GA can be used for several optimization problems. In particular, GA can be used for obtaining minimum number of PMUs required for complete system observability considering one line or one PMU outage and obtaining the optimum placement to locate these PMUs for getting maximum redundancy in observability (Bedekar.PP *et al*., 2011). This technique could be preferred for different sized systems. The GA can also be used for placement of PMUs to determine the fault location. Accuracy of locating the fault is increased using GA (Germian.SS *et al*., 2008). It can also be extended for detecting bad-data of state estimation problem at decomposition and for solving the state estimation problem on the basis of robust criterion using test equations. (Kolosok. I *et al*., 2014). By this the accuracy of the objective and efficiency increases. As a result, the optimization gives an economic reliability for the installation and maintenance. The literature studies have confirmed that GA has extensive features in the optimization field.

Here, GA is handled for optimal placement of PMUs. GA is an iterative process and initially starts with the population size and the fitness evaluation of the algorithm (Aminifar.F *et al*., 2009). The fitness function carried out in this paper is,

$$\min \ f = aN_{PMU} + b(N_h * N_{PMU}) \qquad (1)$$

Here, N_{PMU} is the number of PMUs in the system obtained from the information of chromosome. N_h is the number of unobservable buses that has incomplete information of the measuring quantities.

Then chromosomes are created based on the result to be attained for the observability problem. The chromosomes that are produced in a random manner are binary in nature. These chromosomes will have information with various PMU locations. For an instance, if a bit in a chromosome has value of '1', then PMU is located at that particular bus or location. Else, a bit having '0' expresses that PMU is not present at that bus. Selection of parent chromosomes is done to generate the fittest offspring. To produce the best offspring the parent chromosomes undergoes crossover and mutation process. The newly generated younger ones are placed for the population. The algorithm runs until the stopping criterion is attained and it turn up with a better solution for the optimal placement.

Combined Optimal Placement For Complete Observability:

Combined optimal placement of Phasor measurements units and traditional flow measurements recognizes the complete observability of the Power system with several conveniences. This type of placement assures the reduction of both PMUs and flow measurements placed in a particular network (Rajesh Kavasseri *et al*., 2010). Also, it challenges the problems faced with contingencies, cost and observability (Ali Enshaee *et al*., 2012).

Problem Formulation For The Proposed Method Under Contingency:

Step 1: For the Combined optimal placement problem, it is essential to acquire the knowledge of network topology. The bus connections within the network are easily predictable using connectivity matrix. Form connectivity matrix A.

Connectivity matrix can be given as, $A_{i,j} = \begin{cases} 1 & \text{if i = j} \\ 1 & \text{if i is directly connected to j} \\ 0 & \text{else} \end{cases}$

Step 2: Get the optimal placement of PMUs from Genetic algorithm using the fitness function mentioned at equation (1).

Step 3: Find the PMU in which failure has occurred and it is denoted as PMU_{loss} and the bus where it is located is bus_l.

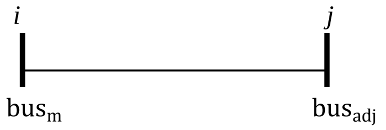
Step 4: Find adjacent buses that are connected to the bus_l with the help of connectivity matrix A.

Adjacent buses of $bus_l = A_{l,j}$ where j=1, 2, . . . N.

Step 5: In the set of adjacent buses, locate a single bus which is connected to any other PMU. Denote the bus as bus_m and hence, the values of it is measured and known.

Step 6: Select the adjacent buses that are not directly connected to at least one PMU which is denoted as $bus_{adj} = [\ bus_{adj1}, bus_{adj2}, \ldots, bus_{adjn}]$ where, n is number of with unknown data.

Step 7: Place the conventional flow measurements on the lines between bus_m and $bus_{adj}(1)$.



(1)

Where, i is the sending end and j is the receiving end. The voltage phasor of bus_m or sending bus is used to determine the current phasor of the receiving end j. This could be found from the relation,

$$V_i I_{ij}^* = P_{ij} + jQ_{ij} \quad (2)$$

In which, real power P_{ij} and reactive power Q_{ij} are measured from the conventional flow measurements. From the equation (2), the voltage phasor of receiving end can be found from the relation (Rajesh Kavasseri *et al*., 2011),

$$V_j = V_i - Z_{ij} I_{ij} \quad (3)$$

Where, V_i is the voltage phasor of sending end. V_j is the voltage phasor of the receiving end. Z_{ij} is said to be impedance of line i-j.

Step 8: Conventional placement is to be done until all the buses in $\mathrm{bus_{adj}}$ have known information. In other words, the step 7 is repeated until $\mathrm{bus_{adjn}}$ is reached.

Thus, the line parameters and voltage phasor of one end is sufficient to determine the parameters of the other end of the line. Here, the combined or mixed placement of the PMUs and conventional flow measurement units are placed to check the observability of the power network.

RESULTS AND DISCUSSION

The placement technique using genetic algorithm is tested on standard IEEE 30 bus system and IEEE 118 bus system. The numerical results obtained from the GA are listed in Table.1 and Table.2. From the results, the power systems have their optimal number of PMUs to be located to enhance observability. Also, the optimal locations of the PMUs are attained by solving the fitness function. The results are obtained under two criteria. They are including the zero injection buses and excluding the zero injection buses of that particular bus system. The numerical results for GA excluding the zero injection buses are given in Table.1. The numerical results for GA including the zero injection buses are given in Table.2.

Table 1: Pmu Locations Using Ga Excluding Zero-Injection Buses

Bus system	Number of PMUs	Location of PMUs
IEEE 30 bus system	10	2, 4, 6, 9, 10, 12, 15, 19, 25, 27
IEEE 118 bus system	32	3, 5, 9, 12, 15, 17, 21, 23, 25, 28, 34, 37, 40, 45, 49, 53, 56, 62, 64, 69, 71, 75, 77, 80, 85, 86, 90, 94, 101, 105, 110, 114

Table 2: Pmu Locations Using Ga Including Zero-Injection Buses

Bus system	Number of PMUs	Location of PMUs
IEEE 30 bus system	7	2, 3, 10, 12, 18, 24, 27
IEEE 118 bus system	29	3, 8, 12, 15, 17, 20, 23, 29, 34, 40, 45, 49, 52, 56, 62, 65, 70, 75, 77, 80, 85, 87, 89, 92, 96, 100, 105, 110, 114

The optimal placements of PMUs are discussed with GA and results are gathered. In this occurrence, if there is any abnormal condition with a contingency such as loss of single PMU then the situation is handled by the usage of conventional flow measurement units. In this proposed work, the placement technique of combined placement of PMU and conventional flow measurement units are discussed. The combined optimal technique deals with placing the conventional flow measurement units at the location of PMU which has the loss of working. To avoid the state of incomplete observability and to reduce the number of PMUs this technique is used. This proposed work is carried under a systematic methodology. The numerical results for combined optimal placement technique are listed in Table.3 and Table.4. This method is also categorized under the criteria of including zero injection buses and excluding zero injection buses.

Table 3: Combined Optimal Placement Locations Excluding Zero-Injection Buses

Bus system	PMU failure (Assumption)	Remaining PMU locations	Number of PMU's	Lines in which flow measurement units to be placed	Number of flow measurement units
IEEE 30 bus system	25	2,4,6,9,10,12,15,19,27	9	27-25, 25-24, 25-26	3
IEEE 118 bus system	110	3, 5, 9, 12, 15, 17, 21, 23, 25, 28, 34, 37, 40, 45, 49,53, 56, 62, 64, 69, 71, 75, 77,80, 85, 86,90,94,101, 105,114.	31	103-110, 110-109, 110-111, 110-112	4

Table 4: Combined Optimal Placement Locations Including Zero-Injection Buses

Bus system	PMU failure (Assumption)	Remaining PMU locations	Number of PMU's	Lines in which flow measurement units to be placed	Number of flow measurement units
IEEE 30 bus system	27	2,3,10,12,18,24	6	25-27, 27-28, 27-29, 27-30	4
IEEE 118 bus system	56	3,8,12,15,17,20,23,29,34, 40,45,49,52,62,65,70, 75,77,80,85,87,89,92,96, 100,105,110,114	28	54-56, 56-55, 56-57, 56-58, 56-59	5

The results are obtained for combined optimal placement technique for the single PMU loss contingency. The PMU in which the failure has occurred is taken as assumption for understanding purpose. The papers of Ali Enshaee *et al*., 2012 and Aminifar.F *et al*., 2010 discusses the contingencies that occur in the PMU placement. In these papers, the optimal placement is taken for complete observability of a network. Also, they have illustrated the procedure to handle the situation of single PMU loss and the placement technique is managed with the other alternative PMU placement. This increases the number of PMUs that are used for complete observability. As a result, it increases the installation cost of the measurement units. Here the proposed method deals with the combined optimal placement of both the PMU and conventional flow measurement unit. The contingency case of single PMU loss is handled with the placement of conventional flow measurement units after the occurrence of PMU failure. By this the number of units to be placed in the given power system will be reduced and as a consequence the cost is minimized. The number of units required in the proposed method for the sample systems are compared with the already published literature (Ali Enshaee *et al*., 2012 and Aminifar.F *et al*., 2010) and given in Table.5. From the table it is clear that the number of PMUs required in the proposed method is drastically reduced. Correspondingly, it was noted that full observability can be attained with fewer PMUs in a combination of conventional flow measurement units for the condition of single PMU loss. Also, the operating time for the execution of the algorithm is mentioned in the Table.6.

Table 5: Comparison Of Number Of Pmus Between Proposed Method And Reference Papers

Bus system	Proposed method (From Table 4)	Ali Enshaee *et al*., 2012	Aminifar.F *et al*., 2010
IEEE 30 bus system	6 PMUs and 4 Flow measurement units	14 PMUs	15 PMUs
IEEE 118 bus system	28 PMUs and 5 Flow measurement units	61 PMUs	63 PMUs

Table 6: Execution Time

Bus system	Combined optimal placement method
IEEE 30 bus system	1.41 seconds
IEEE 118 bus system	2.54 seconds

Conclusion:

Placement issue is one of the difficulties experienced by wide area monitoring systems. Optimal placement is a way to handle this hurdle. In this paper, the optimal placement and combined optimal placement of PMU has been presented for the system observability. In particular, Genetic algorithm is acquired for the optimal placement technique of PMUs under complete observability. Also, an implementation of a new method of combined optimal placement technique for PMUs and flow measurement units are executed for the condition of single PMU loss. The technique is tested for both the conditions such as, including zero-injection buses and excluding zero-injection buses. These methods are implemented in standard IEEE 30 and 118 bus power systems and the results are tabulated. The conception establishes power system observability and reduction of number of PMUs. Consequently, it results in minimization of a reasonable cost of the project. This method can also be implemented for all complex structured power systems.

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